

A LASER-BASED ICE SHAPE PROFILOMETER FOR USE IN ICING WIND TUNNELS

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SUMMARY

A laser-based profilometer was developed to measure the thickness and shape of ice accretions on the leading edge of airfoils and other models in icing wind tunnels. The instrument is a hand held device that is connected to a desk top computer with a 10 meter cable. It projects a laser line onto an ice shape and uses solid state cameras to detect the light scattered by the ice. The instrument corrects the image for camera angle distortions, displays an outline of the ice shape on the computer screen, saves the data on a disk, and can print a full scale drawing of the ice shape. The profilometer has undergone extensive testing in the laboratory and in the NASA Lewis Icing Research Tunnel. Results of the tests show very good agreement between profilometer measurements and known simulated ice shapes and fair agreement between profilometer measurements and hand tracing techniques.

INTRODUCTION

The NASA Lewis Research Center is conducting research on aircraft icing. Icing wind tunnels are often utilized to study the effects of ice formation on wings and other aircraft components. One such wind tunnel is the NASA Lewis Icing Research Tunnel¹ (IRT). During wind tunnel tests, one quantity that often needs to be measured is the thickness and shape of ice accreted on aircraft components. The ice shapes vary widely in form depending on tunnel conditions: from smooth rime ice shapes to complex glaze ice with detailed structures varying in size from tenths of millimeters to several centimeters (fig. 1). An optical technique developed to measure these ice shapes is the subject of this report.

This report is organized in four sections. First, traditional measurement techniques are reviewed and their drawbacks are discussed. Then the requirements of an "ideal" ice profile system are considered. Next, details of the system that was built are explained, including its physical description, engineering requirements, programming considerations, operation, and accuracy. Finally, future development of the instrument will be outlined.

TRADITIONAL MEASUREMENT TECHNIQUES

Traditionally, several techniques have been used to characterize ice shapes. One technique is to photograph the ice shape. However, this method is only useful to make a qualitative assessment of the ice shape and structure. Plaster casts have also been used, but such techniques are labor intensive and can be inaccurate. Hand tracing is probably the most common method for measuring the ice thickness.

Hand traces are made in the IRT between icing runs. After the ice has formed, the tunnel is brought down to idle and technicians enter the tunnel. The section of ice that is to be measured is determined and a hot aluminum block is pressed against the ice near the region of interest. The block is in the shape of the airfoil and it cuts a slot in the ice (fig. 2). The block is then removed and a cardboard tracing square is inserted in the slot. The cardboard is held firmly against the ice and a pencil is used to trace the ice shape onto the cardboard.

This technique has several drawbacks. First, it is labor intensive because it requires two technicians: one to hold the card in place and a second one to do the tracing. A careful tracing can take five to ten minutes, including the time required to melt the ice with the block. Also, an additional step of digitizing the pencil tracing is often done to store the results on a computer. The accuracy of this method is also questionable. Hand traces of identical ice shapes by different people usually vary by several millimeters because of differences in tracing techniques. These differences include variations in the angle the pencil is held and deviations when tracing over difficult regions. For example deep recesses inaccessible to the pencil can be traced differently by different people. Also, tracing over regions containing fragile ice projections can be traced differently. The very act of melting the ice with the aluminum block affects the shape of the ice that is to be measured. Also, this method is a destructive measurement and therefore it precludes doing a time history of an ice shape. After the measurement is made, the remaining ice must be cleared off and a new shape must be accreted.

INSTRUMENTATION REQUIREMENTS

The "ideal" ice profile instrument would have a number of features. First, it would be a remotely operated instrument or at the very least it would minimize the time required for a technician to be in the tunnel to make the measurement. It would be a nondestructive technique so that measurement of the ice could be made at various stages of growth. The instrument should be able to measure all the way around the ice shape including the front as well as the left and right sides. Ideally the measurement should give three dimensional results rather than one slice. It should store results on a computer for easy archival and should be easy to operate with menu driven choices on the computer. Also, it should be accurate, repeatable, and be able to resolve the smallest features on the ice shape.

DESIGN CONSIDERATIONS AND PHYSICAL DESCRIPTION

The ice profile instrument that was developed at NASA Lewis is a portable, laser based instrument as shown in figure 3. The principle of operation of the instrument is to use lasers to project a thin marking line on the ice, then to image this line with a solid state camera. With the proper calibration, the image of the laser line gives an accurate measurement of the ice thickness.

The two most important aspects about the design of the instrument were the choice of lasers and the choice of cameras. Red emitting (670 nm wavelength) diode lasers were chosen because they come in a very small package which includes the necessary lenses to focus the beam into a fan shape that can project a thin red line on the ice. They are low power (< 2 mW), relatively inexpensive,² and they can be powered with one 9 V transistor-type battery for up to 8 hr. Four lasers are used to provide even illumination to all sides of the ice shape and also to help reduce any zones where small ice projections could cause shadowing of the laser line in adjacent regions.

Choice of an appropriate solid state camera was another important consideration. The camera needs to be focused on a very thin but quite bright laser line that is scattered from the surface of the ice. Traditional CCD cameras (charge coupled devices) are ill-equipped to image bright objects in a dark background because of a phenomena called blooming. Blooming occurs in a CCD when a pixel gets saturated with light. The photons entering the CCD array are converted into electrons and stored at a given pixel location during the exposure period. If the illumination source is intense or if the exposure period is longer, too many electrons collect at a pixel location and they spill over into adjacent pixels and the image resolution is reduced. Alternatives to CCD-type cameras are CID-type or charge injection devices. Because of the way CID cameras store and move charge,³ they are less susceptible to blooming. A CID camera manufactured by CIDTEC⁴ was chosen. The camera has a small body (a cube approximately 50 mm on a side), and has a resolution of 512 × 512 pixels. The body of the camera is attached to an electronic box with a 10 m cable which makes the camera ideal for remote operation. Three cameras were needed so that the ice shape could be viewed from the front as well as the left and right sides, thus enabling a complete view of the ice shape.

A frame grabber is utilized to interface the cameras with the computer. The important factors that governed the choice of a frame grabber board included one that could accept input from three cameras simultaneously, supported the progressive scan format of the CID cameras, and provided source code and software libraries so that a custom computer program could be written to operate the system. Other factors included support of higher resolution computer graphics (SVGA) and the ability to view live images on the computer screen without the need for an additional monitor. A frame grabber that meets all of these criteria is manufactured by Dipex.⁵ Additionally the Dipex board has a digital IO port. This facilitated use of an external trigger source to activate the system remotely

and also the port was useful because it allowed a software switch to turn on and off the lasers at the appropriate times.

The camera lenses chosen were commercial C-mount type with a focal length of 16 mm. The lenses came equipped with a variable focusing ring and a variable stop. Because there was ample illumination from the lasers, the lenses could be stopped down to give a large depth of field without sacrificing image brightness. Set screws were added to the lenses to prevent their settings from inadvertently being changed.

The computer available for this project was a 386 33MHz, IBM compatible, desk top computer. Dipex recommended using a SVGA video board manufactured by ATI⁶ for the video display to avoid any possible incompatibilities.

The optical and electronic components described above were all commercially available. Conversely, the mounting hardware was custom designed and manufactured at NASA Lewis. Aluminum was chosen because it is light weight and easy to machine. The laser mounts consist of a cylindrical groove machined into two rectangular aluminum blocks (fig. 4). When the blocks are bolted together they hold the laser diode firmly in the cylindrical groove. By loosening the blocks slightly, the laser can be turned so that the beam can be rotated to a horizontal position. This assembly sits on top of two rectangular blocks that are bolted together at the front and back and have a 2 mm rubber spacer sandwiched between them. The vertical position of the laser line can be adjusted by tightening or loosening either the bolt in front or back. The rubber spacer acts as a kind of spring to allow compression at the front or back of the unit while at the same time it keeps the laser from tipping out of its horizontal alignment. A third degree of freedom allows the laser to be pointed left and right in a horizontal plane. This adjustment was necessary to insure that the beams from adjacent lasers overlap. To achieve this degree of freedom, the entire laser diode mount was fastened to a base plate with a single pivot bolt in the center of the mount.

The mounting arrangement described here was found to be adequate. However, during wind tunnel tests one laser beam would occasionally wander and would need to be adjusted to insure that the beams formed a continuous unbroken line around the ice shape. Such misalignment problems were not difficult to correct and never happened in the laboratory. The problem was probably caused by warping of the mounts brought on by the extreme cold in the IRT.

The camera mounts consisted of aluminum blocks cut at 45° angles. They were fastened with a single pivot bolt to allow precise positioning of the cameras so that the left and right cameras could be aimed perpendicular to the center camera. Any movement of the cameras relative to one another after the system is setup and aligned could cause significant errors in the measurement. To avoid this, the pivot bolt was oversized so that it could be securely tightened with a wrench. This procedure only needed to be done once and the cameras stayed in place indefinitely.

The 45° camera viewing angle was determined after a significant amount of experimentation. Ideally a camera viewing angle 90° to the laser sheet plane would be desirable because this would have the camera looking straight down on the ice shape and would have very little distortion. However, camera angles larger than 45° have two drawbacks. First the laser light scattered at steep angles is not very bright. More importantly the ice shapes are highly irregular and have overhanging ridges that could block the region of interest from view. Decreasing the camera angle below 45° is desirable in that it will decrease the probability of having part of the image blocked by overhanging ice, but the camera angle distortion becomes so significant that the image cannot be reliably corrected. Thus, using the 45° angle represents a compromise between the steep and shallow positions.

The assembly that holds the camera mounts and the laser mounts consists of two flat aluminum plates connected together by four 35 cm long threaded rods. The top plate holds the camera mounts with the cameras aimed down at a 45° angle. The bottom plate holds the laser mounts. Also mounted on this assembly is a momentary push button switch that acts as an electronic shutter release. The whole unit is tethered to the computer through a 10 m light weight flexible plastic conduit that contains the camera cables, power cables for the lasers, and the electronic shutter release cable. The entire instrument is relatively light weight and is easily handled by one person.

Some custom electronics were needed for the instrument. These consisted of a camera control circuit, an electronic shutter release, and a laser power supply circuit. The CID cameras used for this project were all "master" cameras. That is, they each generate their own sync signals that the frame grabber needs to lock onto. Although the Dipex frame grabber has three signal ports for each of the cameras, it only has one sync line input. To solve this problem the three sync signals from the cameras were routed through a data select IC. The digital IO port on the frame grabber was programmed to sequentially send one of three addresses to the data select IC that corresponded to each of the cameras. This allows the sync signals from each camera to be electronically connected to the frame grabber prior to the frame grabber acquiring the image data.

The electronic shutter release consists of a momentary push button switch that is also connected to the digital IO port on the frame grabber. When the button is pushed, it grounds the circuit and the software detects the level change. The software then initiates the necessary steps to complete the frame grabbing procedure.

The laser power supply circuit is also controlled by the digital IO port on the frame grabber. A single IO line from the frame grabber was connected to a logical OR gate. The output of the OR gate was connected to a reed relay that is used to switch on the laser power supply (12 volts DC, 240 mA, modular). Also, a mechanical toggle switch was connected to the other input on the OR gate. This enables the lasers to be turned on without running the software program.

PROGRAMMING CONSIDERATIONS

The software required to run the instrument was developed using three different programming languages. The routines that interface with the frame grabber software were written in C because the software control libraries provided by the frame grabber manufacturer were written in that language. Routines that provide low level video commands for the SVGA board were written in assembly language. These routines were very short subroutines and performed low level functions like initializing the SVGA screen and video screen paging. Assembly language was chosen because ATI, the video card manufacturer, provided sample code segments in assembly language that executed these functions. The QuickBasic programming language was used to provide menu capabilities, run the C and assembly applications, save and display the data, and provide correction to the images that were distorted due to the 45° camera angle.

Processing the images of the ice shapes required distortion correction. The primary distortion was present because the cameras were viewing the ice shape from a 45° angle. This made rectangular objects appear trapezoidal in shape as illustrated in figures 5(a) and (b). Another distortion that was present was caused by the camera lens and is known as barrel distortion. These barrel distortions are only slightly visible in the images. For example in figure 5(b) the horizontal rows are slightly curved rather than straight. Never-the-less, this distortion also needs to be corrected to insure the accuracy of the measurement.

A single method was developed to correct the viewing angle distortions and the barrel distortions. To make the corrections, a test pattern is utilized. The pattern is a grid of small squares as shown in figure 5(a). The size of the squares is small enough so that any distortion within an individual square is negligible but the squares are large enough so that each square can be easily identified by a software routine. The distance between the squares is the same in both directions and is precisely known. The squares are close enough together so that it can be assumed the distortions between any two squares are linear. It is recognized that the distortions over larger distances are not necessarily linear, but they can be approximated by piecewise linear functions.

The correction is performed via a lookup table that takes any given pixel location on a distorted image and maps it into another location that corrects the positional distortions. The lookup table is constructed with the use of the test pattern. The test pattern is placed in view of the camera at the same plane as the laser beams (the lasers however are not activated during this procedure). Next the image of the test pattern is acquired by the camera (fig. 5(b)). Then the image data is scanned by a computer program to find the x-y position of the centroid of each square. The centroid of each square will be referred to as the centroid point. The centroid point that is in the upper left corner of the image is defined as the origin (0, 0). The centroid point located immediately to the right of the origin is located and denoted as centroid point (0, 1). All pixels located between the origin point (0, 0) and the (0, 1) point are located. Each pixel location is assigned a numeric value that is derived from an interpolation based on: (a) the number of pixels between (0, 0) and (0, 1) and (b) the known distance between the center of the squares on the test image. This value is the horizontal offset of any given pixel from the origin. At the same time the horizontal offset is calculated, the vertical offset is also calculated based on the position of the centroid point located immediately below the origin centroid point. The interpolated x-y positional value for each of the 262,144 (512x512) pixels of the image file is saved in a lookup table. For pixels around the outer edge of the image, the value used for the lookup table is calculated by extrapolation from the interior points. There are three lookup tables for each of the three cameras. The process of generating and saving the lookup tables takes about an hour but is completely automated. After the lookup tables are generated, they do not need to be recalculated unless the cameras are knocked out of alignment. Also, since the lookup table is a pixel mapping, it corrects for all positional distortions that can be present in the image, whether they were caused by camera angle distortions or barrel distortions.

Using the lookup tables to correct an image is considerably faster than the initial generation of the table. To correct a distorted image, each pixel on the image is interrogated (i.e. its row, column, and intensity are determined).

Using the row and column information, the computer program locates in the lookup table where that pixel *should* be located in relation to the upper left corner. On the computer display screen, this position is determined in screen coordinates, and the computer screen pixel is set to the same intensity as the image pixel. It takes about two minutes to correct distortions in all 262,144 pixels and to display the processed image. When processing ice shapes this correction time is significantly reduced because the image of the laser line represents a small region of interest. This region typically consists of a string of only several thousand pixels stretching across the image. So the correction of an ice shape image is accomplished in a few seconds.

High pass filtering is employed in order to determine which pixels correspond to the image of the laser line scattered from the ice shape and which pixels do not. The laser line corresponds to the brightest pixels. Thus, only pixels with intensities above a certain threshold are considered for the distortion correction algorithm. To reduce this set of pixels even more, a positive intensity gradient detection algorithm is also applied to the image. For example, after high pass filtering, the pixels that remain form an irregular line that represent the image of the laser beam on the ice shape (fig. 6). This line is typically many pixels thick because some of the light penetrates into the ice. To reduce the thickness of the line, only the pixels that represent the transition from a dark region to a bright region are retained (positive intensity gradient). Pixels that are surrounded by other bright pixels are eliminated (zero intensity gradient) and pixels that are on the opposite side of the line and thus represent the transition from bright to dark are also eliminated (negative intensity gradient). The line that is left is thin and is made up of only a few thousand pixels. It is this array of pixels that is passed to the distortion correction algorithm. Using the positive intensity gradient rather than a mean value of the line was found to be more accurate because it represents the leading edge of the ice shape before the laser beam has penetrated into the ice.

Another image processing issue that had to be addressed was merging the images from the three cameras into one continuous image. To accomplish this, the images from the left and right cameras were each rotated 90° by the software so they showed a perspective that was identical to the central camera (fig. 7). Besides rotating the images, the software also translated them so that overlapping regions would show up at the same location on the final image. The amount of the translation was determined by placing a line drawing in view of all three cameras and using a software routine to determine how large the offset should be to make the images overlap. The x and y offsets were then saved in a file. This procedure is part of the setup process and only needs to be done once.

OPERATION OF THE PROFILOMETER

After the camera software is setup for distortion correction and the image offset is determined, it is necessary to do an end-to-end check of the system. The best way to do this is to use the instrument to trace the outline of a test object of a known diameter. A pipe with an outside diameter of 108 mm (4.25") will serve this purpose. It only needs to be several centimeters long and should be painted a light color so the laser beams will reflect off the surface. Place the pipe in the beams and observe that all four beams form a continuous line on the pipe. If they do not, the positioning screws on the laser mounts should be used to adjust the beams.

After the beams are adjusted, take an image of the pipe using the electronic shutter release on the instrument. After the software routine has corrected and combined the images, they are displayed on the computer screen. First make certain that the outline of the pipe that is drawn is continuous. If it is not, then the software position offset from either the left or right camera needs further adjustment. If the line is continuous, then verify that the diameter shown on the screen is correct (to within about 1 percent). As one last check, print out the image and set the pipe over the top of the page containing the outline. It should be a nearly perfect match. This will give you a visual picture of how well you can expect the instrument to perform.

Using any optical instrument in an icing tunnel such as the IRT requires some added precautions. For example, the instrument should be kept at the same temperature as the tunnel. Bringing it in and out of the tunnel will cause condensation to form and could cause its electronic components to fail. At NASA Lewis, the instrument is kept in an environment box constructed in a window opening inside the tunnel. Since the box sits in a window opening, it does not project into the flow and does not cause any added turbulence. A door on the tunnel side of the box is located where the window normally would be located. The door allows access to the instrument from the tunnel side. The control room side of the box is insulated so that the box stays at nearly the same temperature as the tunnel. A hole in the box on the control room side allows the instrument cable to pass into the control room where the computer is located. The environment box is also purged with dry air to keep the instrument dry during tunnel warm up. This purge however has been only moderately successful to date. After the warm up and shut down phases,

inspection of the interior of the box usually shows evidence of condensation. Probably a higher flow of purge air is needed to keep the box and the instrument totally dry during the warm up phase.

The procedure for measuring ice shapes is a three step process. First, prior to the icing runs, a profile of the model (an airfoil for example) needs to be made so that subsequent measurements of the ice shape can be referenced to this. When making the profile of the model, it is important that some region on model be visible to the laser profile before and after ice buildup. This is used as a reference point between the ice shape and the clean model profile. At first this may appear to present a problem since after an icing run the model would be covered with ice, thus masking the region that is to be used for the reference. However, in practice the ice only accumulates on the leading edge of the model and also as far back as a few centimeters from the leading edge. Generally the images from the left and right cameras show regions further back on the model, in a region that is free from ice. It is this area that can be used for the reference. After the profile of the clean model is taken and saved in the computer, as many icing profiles can be taken as desired. They can all be referenced to the same clean model profile.

The second step for measuring the ice shape is optional, but tends to enhance the image of the laser line if the ice is especially clear and allows the laser light to penetrate into the ice rather than scatter from the surface. We found that spraying the ice with powdered corn starch (i.e. baby powder) will make the laser beam scatter brightly off any ice surface. This makes a very bright and narrow image of the laser line for the software to evaluate. This step requires the tunnel to be brought down to idle after the ice has formed and a technician enters the tunnel and sprays powder on the ice around the region of interest.

The delivery system for the powder consists of a can of compressed air that has a small diameter plastic straw coming out of the nozzle. The straw protrudes through a hole drilled in the side of the container of powder. The can of compressed air and the powder container are attached together. A second hole on the opposite side of the container allows the powder to escape when the compressed air is blown into the powder container. Using this device allows a fine mist of powder to be delivered to the ice that greatly enhances the image of the laser line. The powder forms such a thin film over the ice that it does not adversely affect the measurement.

After the ice is sprayed with the powder the ice measurement can be made. The instrument is removed from the environment box and placed in front of the model that has the ice shape on it. The instrument may be hand held or placed on a tripod if the ice profile at a precise location is needed. In either case, a leveling bubble that is attached to the top of the instrument should be checked to verify that the instrument is measuring a horizontal slice. It takes some practice to use the instrument without a tripod because it must be held level, without movement, and be fairly close to the ice with a tolerance of about ± 1 cm. The advantage of holding the instrument rather than mounting it on a tripod is one of speed. In practice, a technician can spray the model with the corn starch, remove the instrument from the environment box, measure the ice profile, replace the instrument, and exit the tunnel in as little as two minutes. By the time the technician is back in the control room, the ice profile has been saved on the computer's hard disk and the corrected image is displayed on the screen and is ready to be printed if desired.

Samples of several ice profiles are shown in figures 8 to 11. In figure 8 a clean airfoil is shown on the left and the same airfoil is on the right after an icing run. The two profiles were deliberately separated so that the reference marks on both are visible. A software program is used to move one or the other image around so that the reference marks from both images can be superimposed. In this case the reference mark that was used was a black line painted on the airfoil. The black paint reflected very little laser light and therefore left the gap in the line. The gap is used to align the two images. When running the software, "proper" image alignment is determined by the computer operator. The operator can translate either image in the xy direction or rotate either one about the image centroid.

The same two data sets are shown in figure 9 after they have been superimposed. Note that some gaps in the ice shape are present on the lower right side. This is a result of ice projections blocking part of the view from the camera.

For comparison, another type of ice shape is shown in figure 10. Note that this is about the largest shape that can be measured. The bottom portion is nearly out of the frame and the reference marks at the top are also close to the edge of the frame. One other thing to notice about these printouts is the box around the outside is 140×140 mm. This is included so that if the images are reduced for publication, the actual size can be determined by measuring the size of the box and scaling accordingly.

Figure 11 shows a capability of the ice profiling instrument that is not possible using the hand tracing technique. In this figure the growth of the ice is shown over time. First the clean airfoil was recorded, then the ice buildup was recorded in two minute intervals. Note the ridges at the back part of the airfoil. During this test, a plastic strip was attached to the airfoil to act as the reference mark rather than the black line. Both methods appeared to work equally well.

Instrument Accuracy

We tested the instrument in the laboratory using several simulated ice shapes. We also tested the profilometer in the wind tunnel and used the hand tracing method for comparison.

The shape that provided the most quantitative data to assess the instrument's accuracy was a pipe with a nominal outside diameter of 108 mm (4.25"). The procedure for gathering the data was as follows: a) place the pipe in the field of view of the instrument; b) record the diameter as measured by the instrument; c) remove the pipe; d) repeat the procedure. The reason for removing the pipe and then replacing it was to be sure that we were not always analyzing the exact same image with the software. The measured diameter for ten trials ranged from 107.1 mm to 108.0 mm with the average being 107.6 mm. This is a percent difference of 0.4 percent. Thus, we quote the instrument accuracy as "better than 1 percent".

A more qualitative assessment of the instrument accuracy was performed with a plaster cast of an ice shape. The cast was cut with a band saw and sanded down so as to form a smooth flat surface. The plaster ice shape was then set on a piece of photographic film and light was allowed to expose the part of the film that was not covered by the plaster shape. This contact print was the standard which we compared with the laser profile instrument data and is shown in figure 12. Note that the laser instrument data has been offset down and to the left for clarity. Also note that as with real ice shapes, some of the data is missing because projecting material is blocking part of the cameras' view.

Comparisons with hand tracing of actual ice shapes were less favorable than the laboratory comparisons. Several comparisons are shown in figures 13 to 15. There could be a number of reasons for the discrepancies. First, the hand tracing has its own set of errors associated with it. Second, it is impossible to do the laser trace at exactly the same location as the hand tracing. Third, the laser tracing method may have some inaccuracies associated with it that has not been detected by laboratory testing.

Whether the discrepancies are caused by errors in the hand tracing method or some other mechanism, is not known for certain. However, in light of the fact that the hand tracing technique requires melting the ice very close to the region of interest, and this process in all likelihood alters the very quantity that is to be measured, we believe the laser tracing instrument is making a measurement that is more accurate than the hand traces.

FUTURE DEVELOPMENT

Potential future work includes further automation of positioning and improvements in the angle distortion correction software. Instead of having the instrument placed in front of the airfoil manually, a linear positioning system could be used to bring it down from a recessed area above the model. This would also enable a series of ice profiles to be collected and assembled into a three dimensional view of the ice shape. Also some different angle distortion correction algorithms might be employed. For example the current system requires a two step process to first determine the distortion correction and second to determine the offset to the left and right cameras. The latter of these assumes the left and right cameras are aimed perpendicular to the center camera. A more general method might be to let the left and right cameras assume any orientation, possibly pointing outward to accommodate wider fields of view. To allow this to occur, determination of the distortion correction and determination of the offset could be done at once. This would be performed entirely in software.

CONCLUSIONS

An ice profilometer was developed to measure ice shapes on the leading edge of airfoils and other models in icing wind tunnels. Many of the initial requirements for an "ideal" ice measuring instrument were met. The instrument can be remotely operated, it uses a nondestructive technique, it can measure ice at various stages of growth, it can view the ice on three sides, it can store and display data via a desk top computer, and it can be operated by a technician with a minimum amount of training. Also, with additional hardware it is capable of producing three dimensional images. The only requirement not satisfied was the ability to measure the very smallest features in the ice.

Tests show agreement with known simulated ice shapes to within 1 percent. Agreement between the instrument and hand tracing techniques is fair. Further testing should be performed with the instrument in an icing wind tunnel to determine if these discrepancies with the hand tracing technique are a result of instrument errors or if they are inherent problems with the hand tracing technique.

REFERENCES

1. Soeder, R.H.; and Andracchio, C.R.: "NASA Lewis Icing Research Tunnel User Manual," NASA TM-102319 (1990).
2. Power Technology, Inc., Little Rock, Arkansas, (501) 568-1995. Visible laser diode modules with line generating optics (model PM08L401): \$400.
3. Janesick, J.R.: "Guest Editorial: Charge Coupled Device and Charge Injection Device Theory and Application," *Optical Engineering* 26 (10), 963-964 (1987). Note: This issue of *Optical Engineering* is dedicated to CCD and CID devices.
4. CIDTEC, Liverpool, New York, (315)-451-9410. CID camera (model 2250D2) with power supply and 10 meter cable: \$3200.
5. Dipex Technologies, Inc., Ottawa, Ontario, Canada, (613) 596-4942. Frame grabber (P360F-4MB), cable (P360F-CAB-DIN), display board (P360F-DIS/P-SBO): \$5300.
6. ATI Technologies, Ontario, Canada, (905) 882-2600. Graphics Ultra Pro Super VGA Graphics Card: \$529.



Figure 1.—A typical ice shape accreted on the leading edge of an airfoil in the NASA Lewis Icing Research Tunnel.

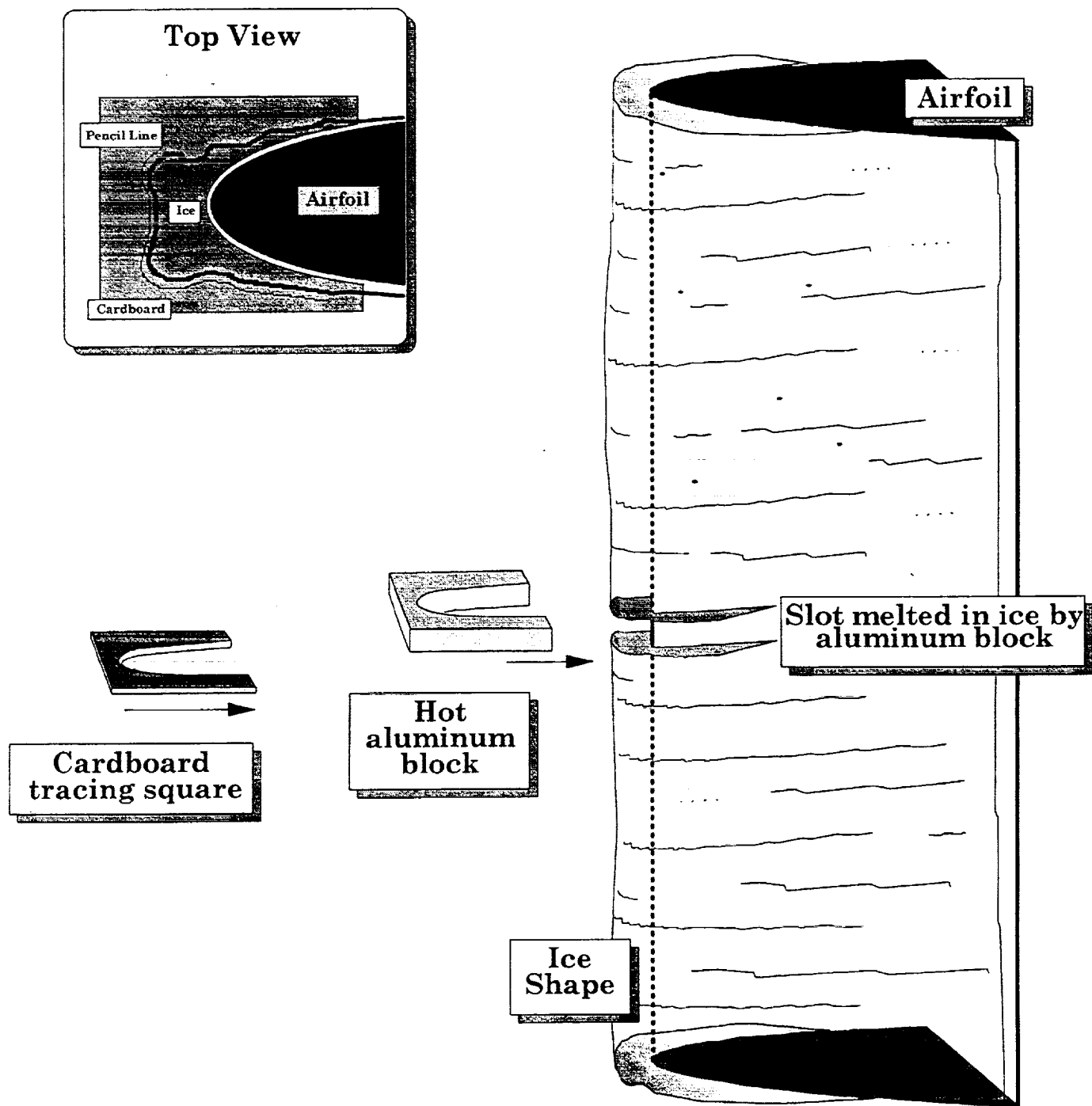


Figure 2.—Procedure for making hand traces of an ice shape. (a) Melt a slot in the ice just below the region of interest. (b) Slip a cardboard tracing square into the melted slot. (c) While holding the cardboard against the ice, use a pencil to trace the ice shape on the cardboard.

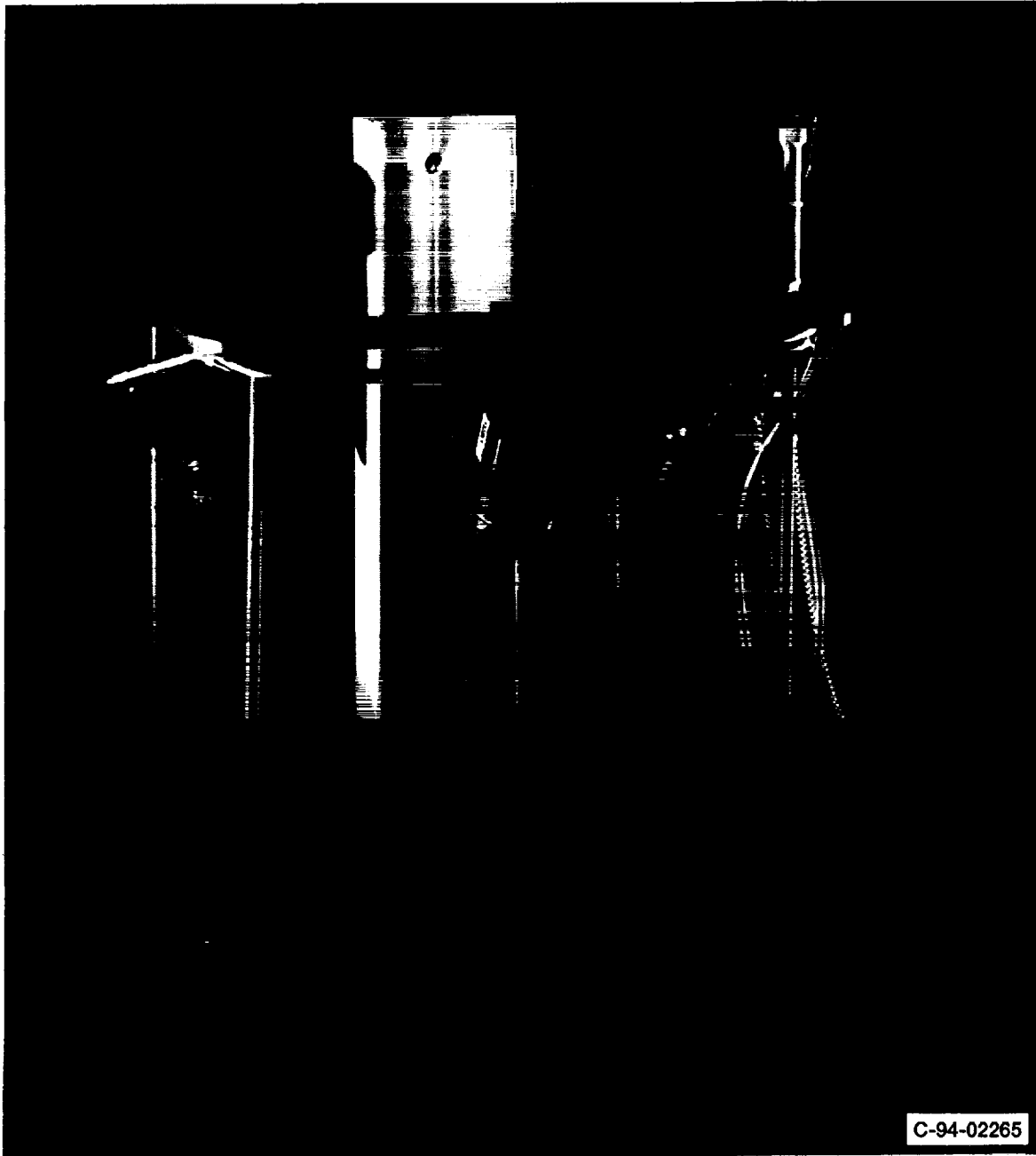


Figure 3.—Photograph of the ice profilometer illuminating a simulated ice shape.

Three degrees of freedom:

- a. rotation**
- b. vertical position**
- c. horizontal position**

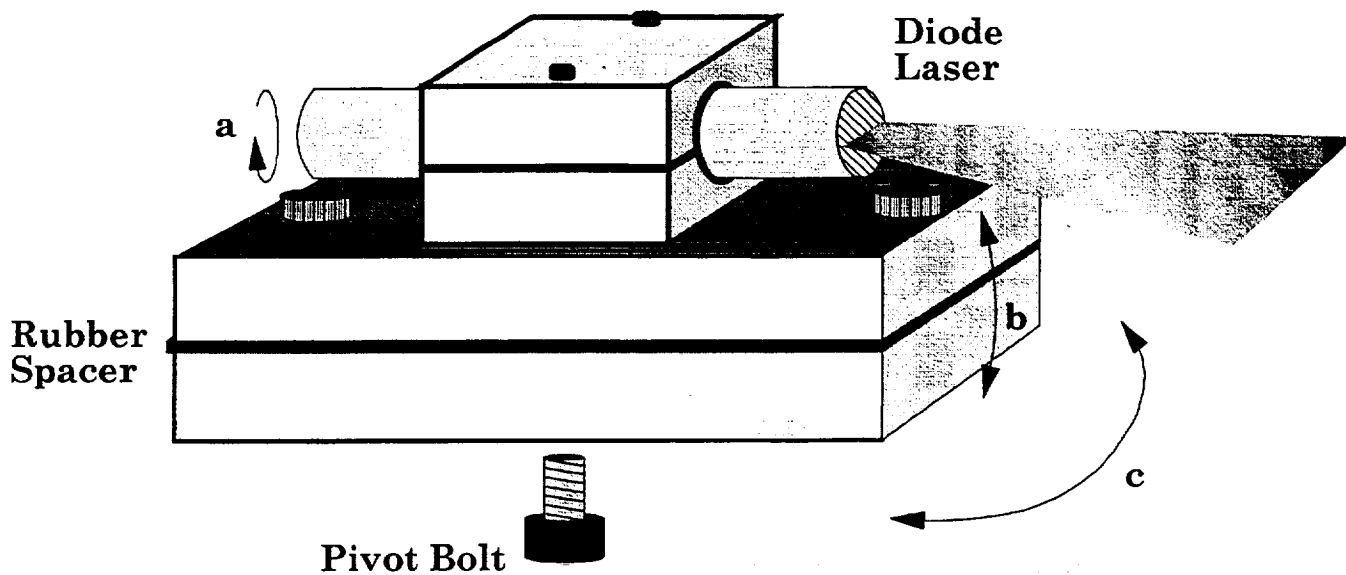


Figure 4.—Laser diode mounts.

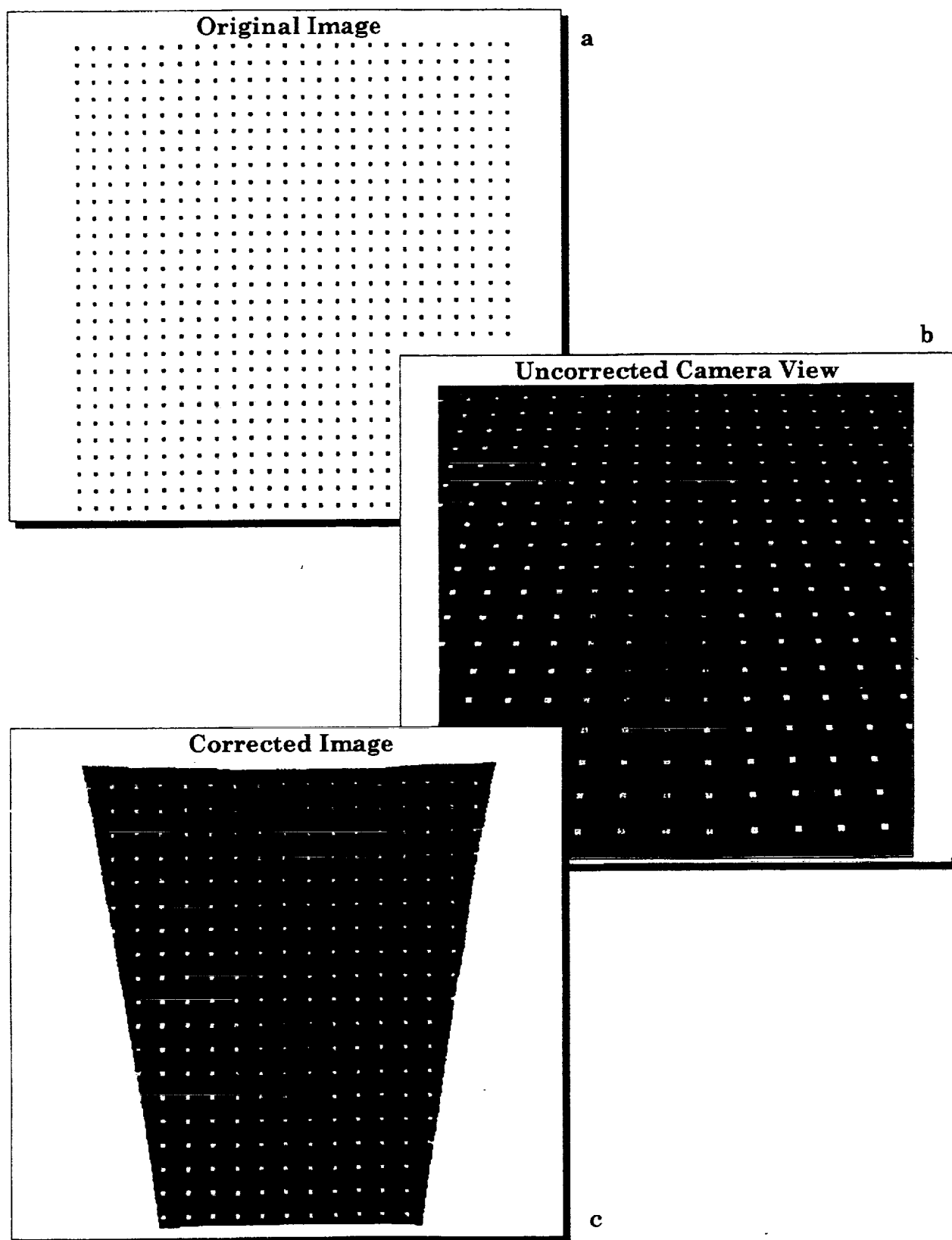


Figure 5.—Distortion due to viewing an image at a 45° angle. (a) A computer drawing containing a series of small squares is used as a "test pattern". (b) The camera view of the test pattern shows severe distortion. (c) After the image is processed the positional distortions are corrected.

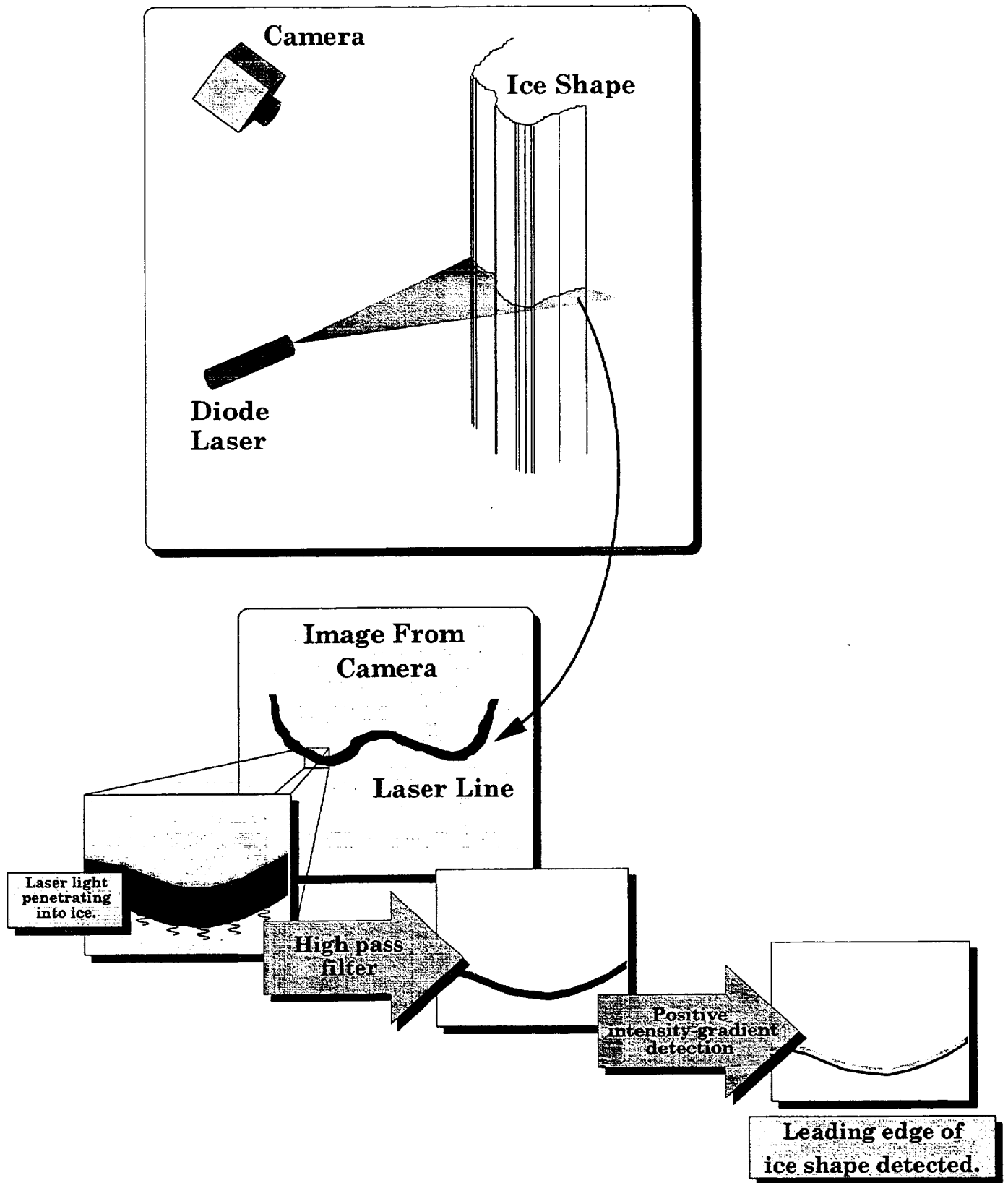


Figure 6.—Filtering the image of the laser line.

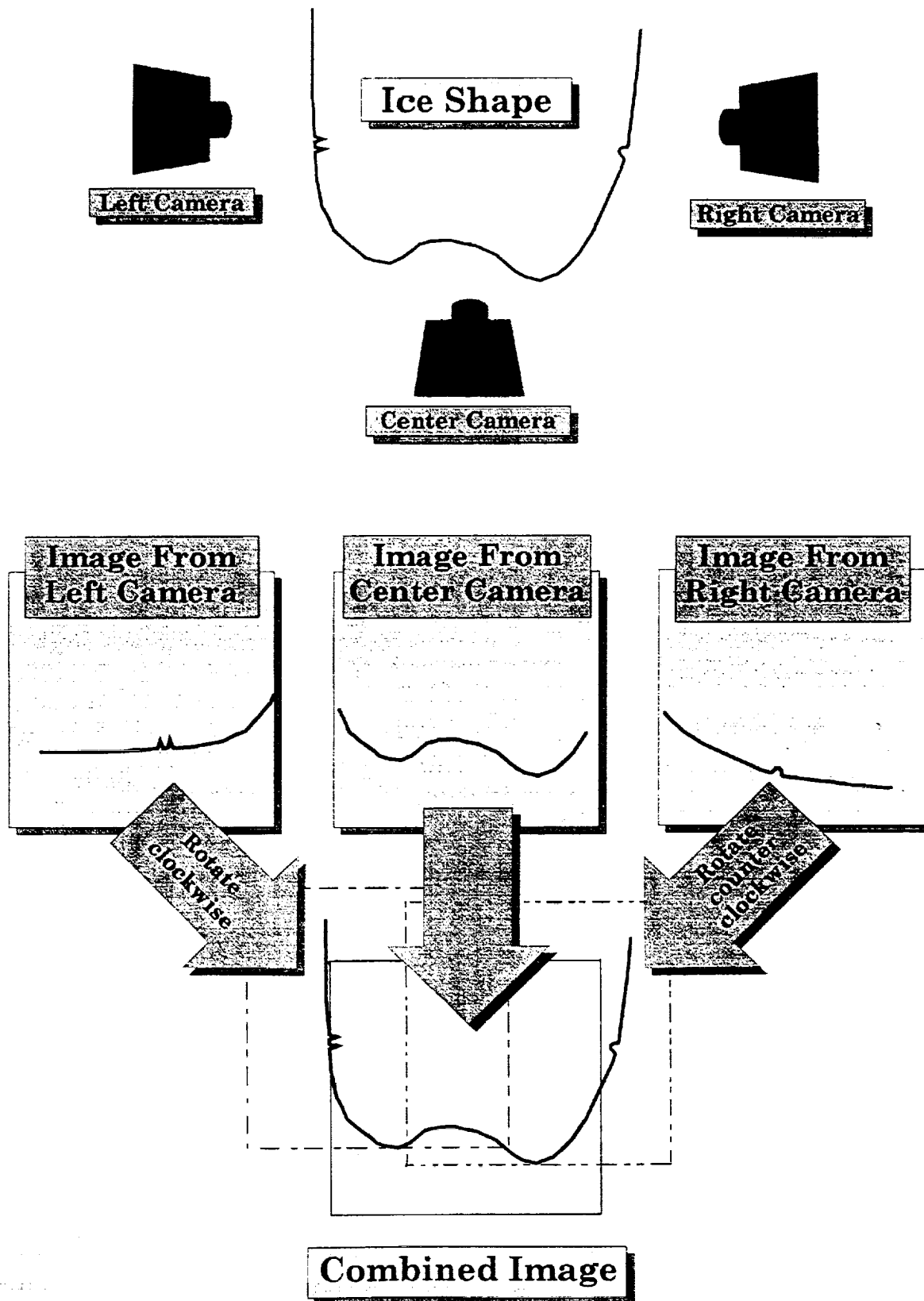


Figure 7.—Rotating and combining the images from three cameras into one image.

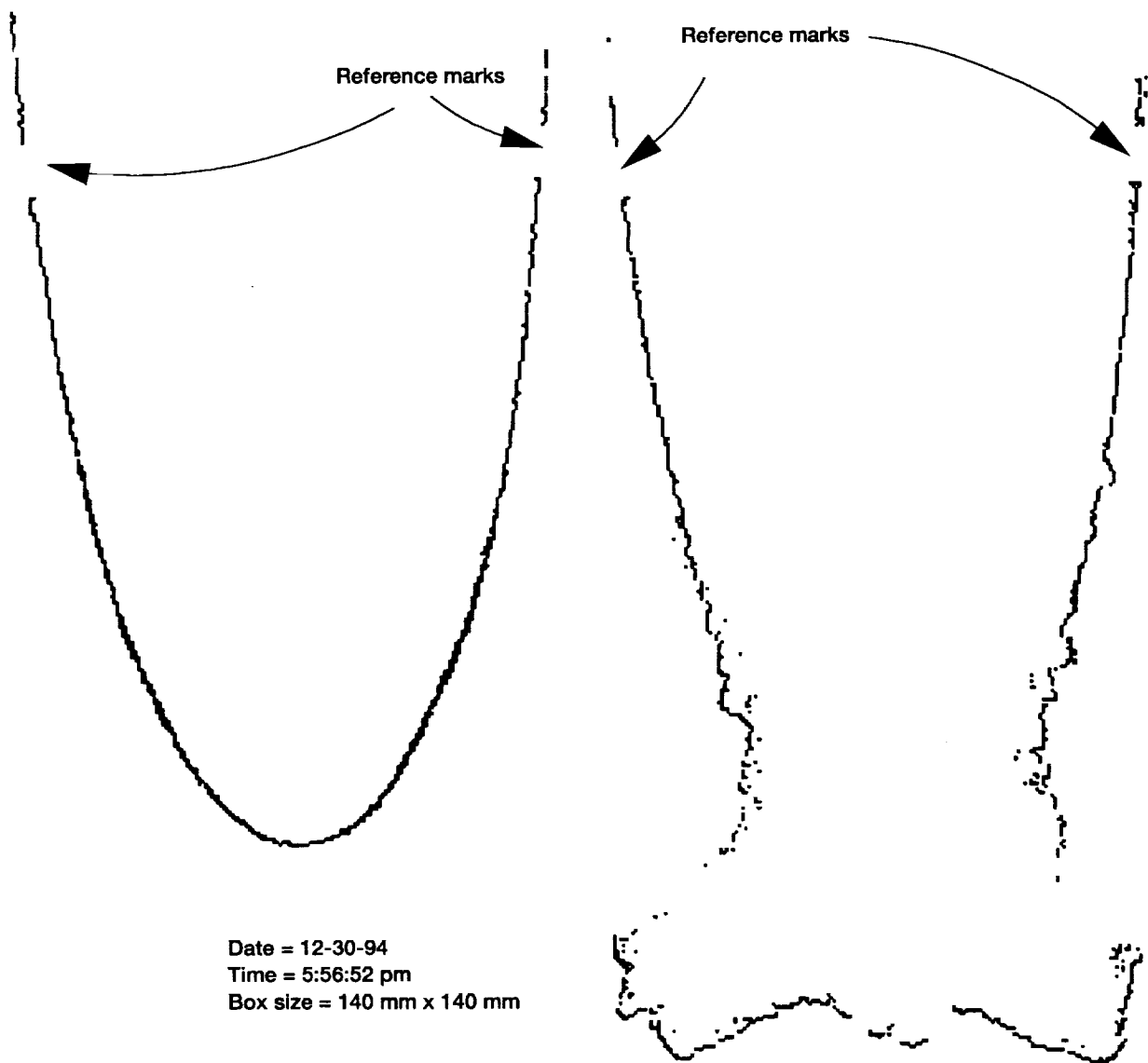
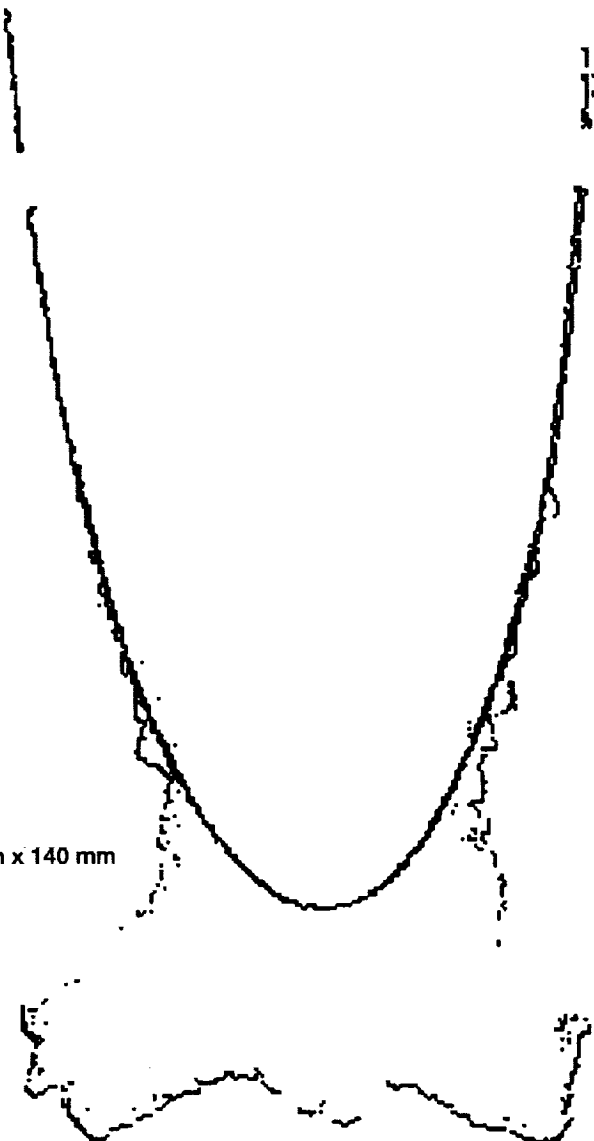


Figure 8.—Laser tracing of a clean airfoil on the left and the same airfoil after ice accretion. Note the reference marks used to align the two images.



Date = 12-30-94
Time = 6:03:42 pm
Box size = 140 mm x 140 mm

Figure 9.—Same images as shown in Fig. 8, but after alignment so ice thickness can be determined.

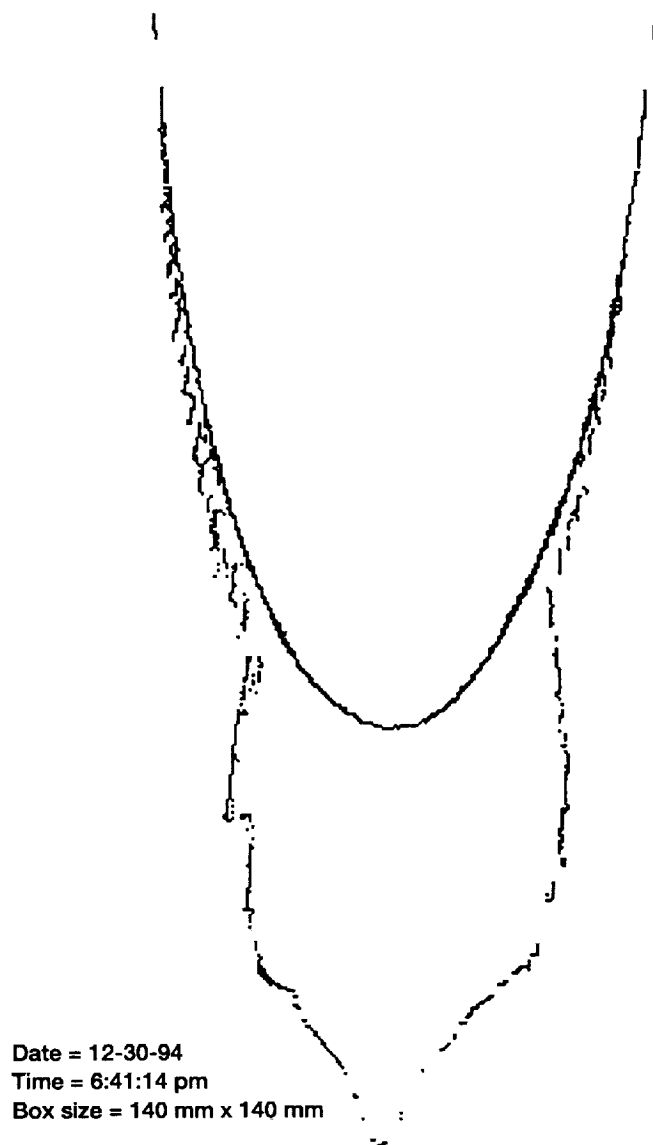
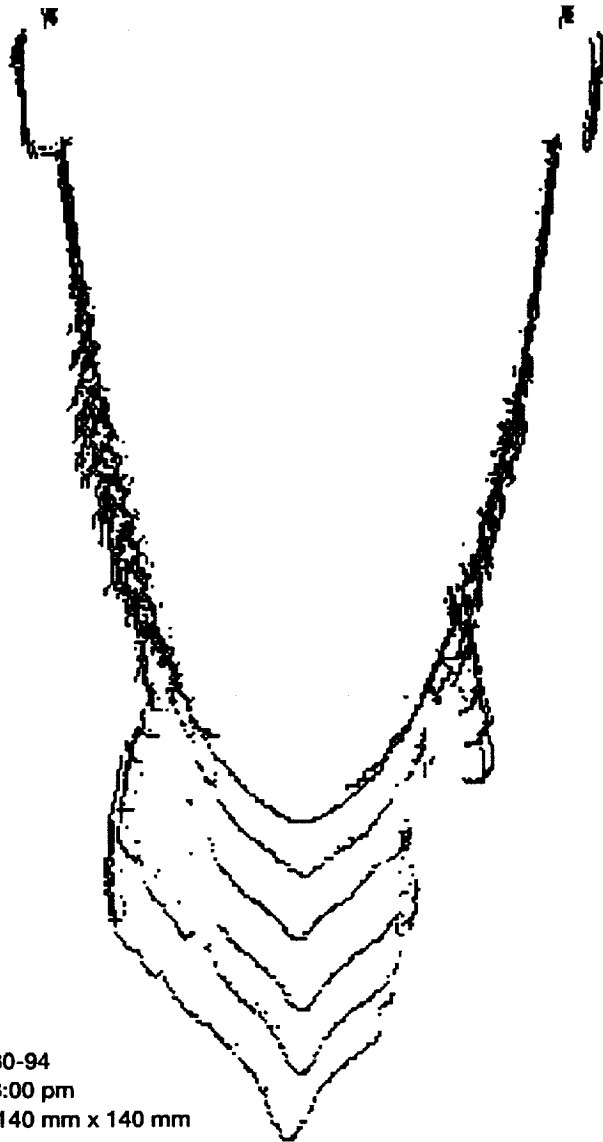


Figure 10.—A large ice shape on the leading edge of an airfoil.



Date = 12-30-94
Time = 6:08:00 pm
Box size = 140 mm x 140 mm

Figure 11.—A series of ice shapes grown over time.

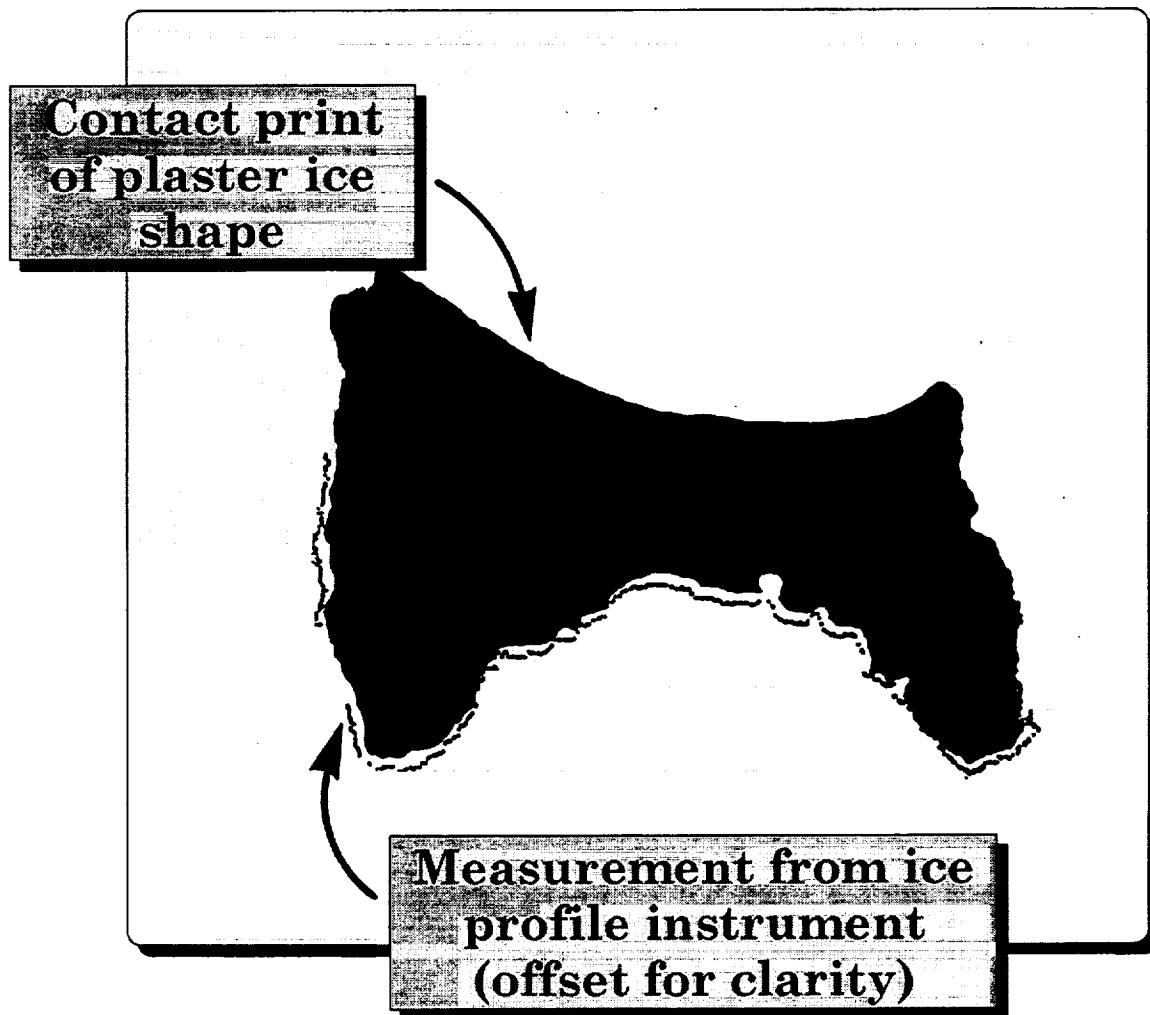


Figure 12.—Comparison of contact print with laser profile.

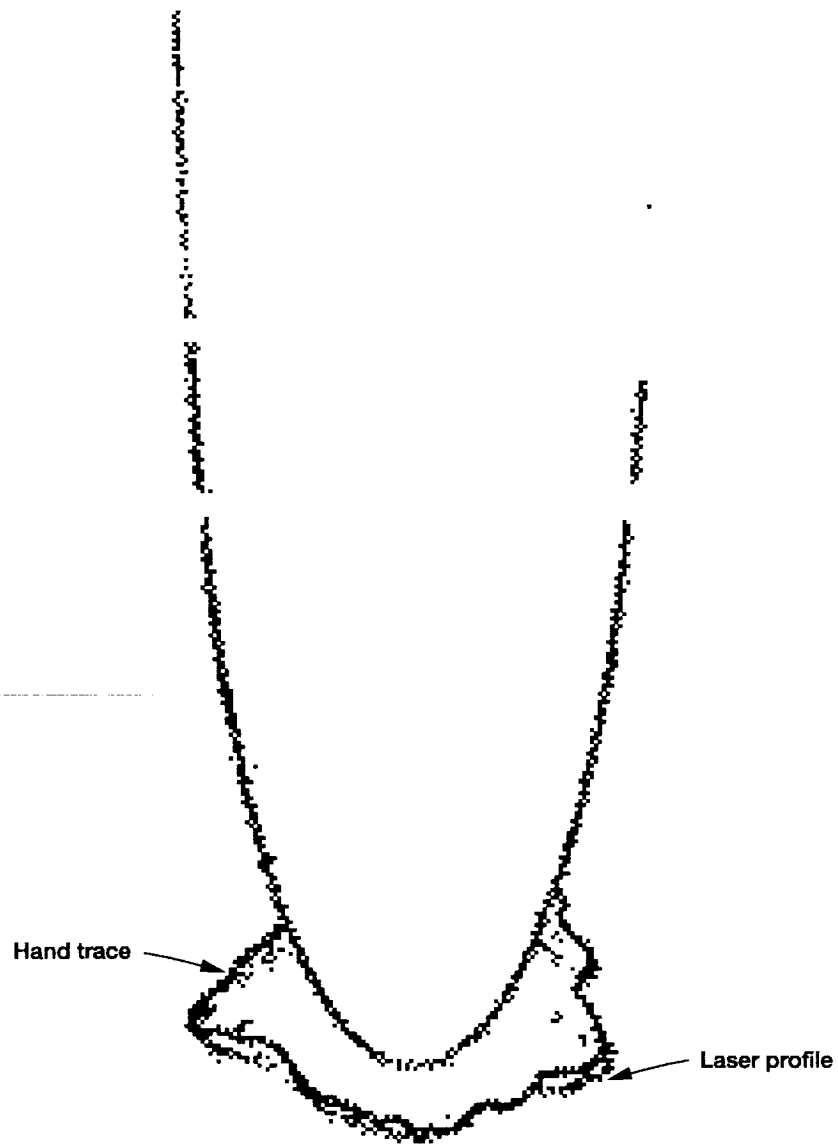


Figure 13.—Comparison of hand tracing with laser profile.

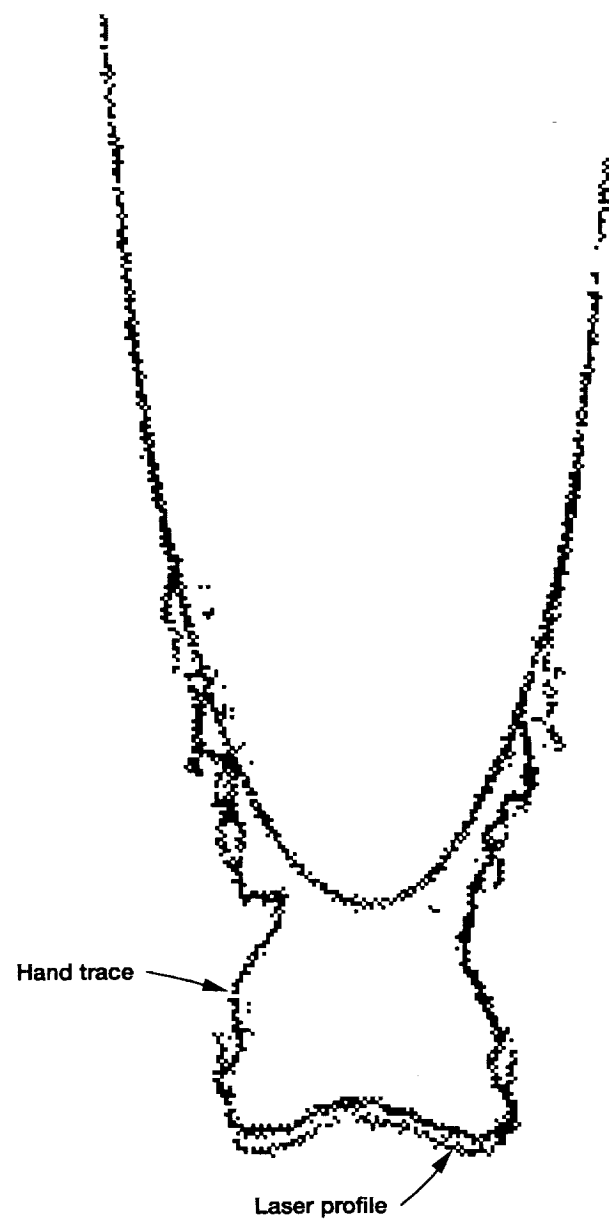


Figure 14.—Comparison of hand tracing with laser profile.

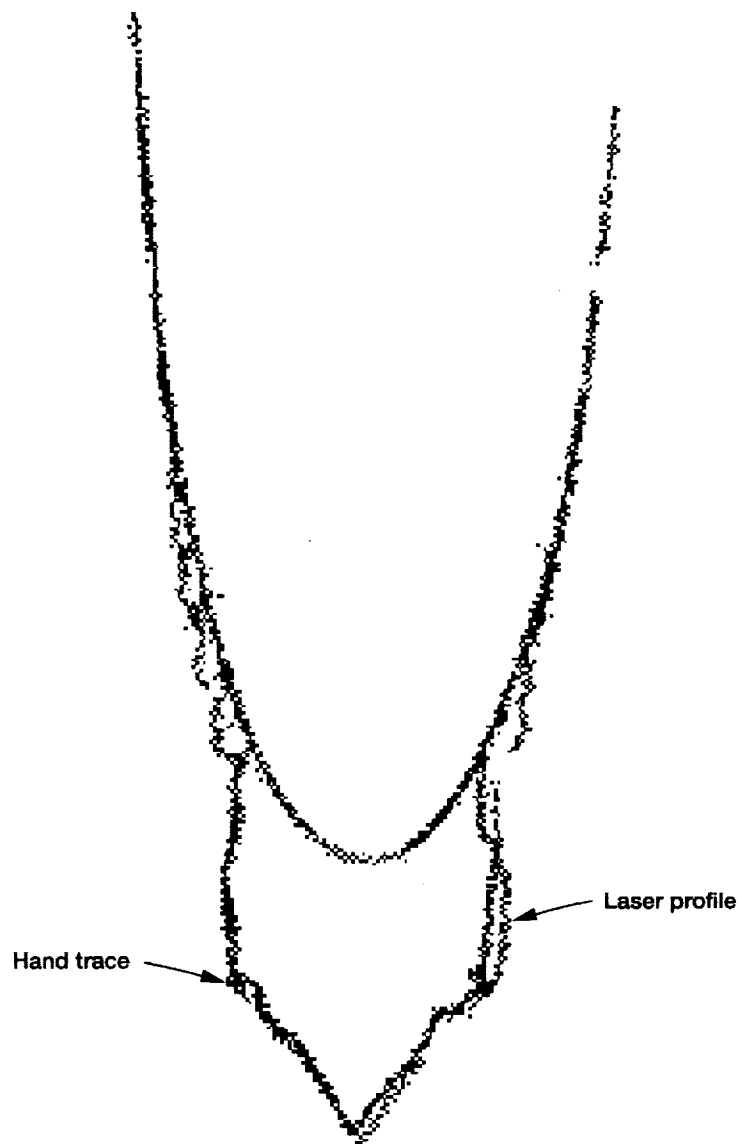


Figure 15.—Comparison of hand tracing with laser profile.

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13. ABSTRACT (Maximum 200 words) A laser-based profilometer was developed to measure the thickness and shape of ice accretions on the leading edge of airfoils and other models in icing wind tunnels. The instrument is a hand held device that is connected to a desk top computer with a 10 meter cable. It projects a laser line onto an ice shape and uses solid state cameras to detect the light scattered by the ice. The instrument corrects the image for camera angle distortions, displays an outline of the ice shape on the computer screen, saves the data on a disk, and can print a full scale drawing of the ice shape. The profilometer has undergone extensive testing in the laboratory and in the NASA Lewis Icing Research Tunnel. Results of the tests show very good agreement between profilometer measurements and known simulated ice shapes and fair agreement between profilometer measurements and hand tracing techniques.				
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